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The *International Review of Mechanical Engineering (IREME)* is a publication of the **Praise Worthy Prize S.r.l.**. The Review is published bimonthly, appearing on the last day of January, March, May, July, September, November.

Published and Printed in Italy by **Praise Worthy Prize S.r.l.**, Naples, November 30, 2015.

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# International Review of Mechanical Engineering (IREME)



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 ISSN: 1970-8734  
e-ISSN: 1970-8742

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SNIP 2015: 0.415 (i)

IPP 2015: 0.386 (i)

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SCImago Journal Rank 2015: Q3

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## Frequency:

published bimonthly, appearing on the last day of January, March, May, July, September, November.

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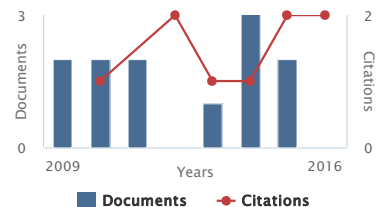
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## Ensemble Kalman Filter with a Square Root Scheme (EnKF-SR) for Trajectory Estimation of AUV SEGOROGENI ITS

Teguh Herlambang, Eko Budi Djatmiko, Hendro Nurhadi

**Abstract** – Results of a study on the development of navigation system and guidance for AUV are presented in this paper. The study was carried to evaluate the behavior of AUV SEGOROGENI ITS, designed with a characteristic length of 980 mm, cross-section diameter of 180 mm, for operation in a 3.0 m water depth, at a maximum forward speed of 1.94 knots. The most common problem in the development of AUVs is the limitation in the mathematical model and the restriction on the degree of freedom in simulation. In this study a model of linear system was implemented, derived from a non-linear system that is linearized utilizing the Jacobian matrix. The linear system is then implemented as a platform to estimate the trajectory. In this respect the estimation is carried out by adopting the method of Ensemble Kalman Filter Square Root (EnKF-SR). The EnKF-SR method basically is developed from EnKF at the stage of correction algorithm. The implementation of EnKF-SR on the linear model comprises of three simulations, each of which generates 100, 200 and 300 ensembles. The best simulation exhibited the error between the real tracking and the simulation in translation mode was in the order of 0.009 m/s, whereas in the rotation mode was some 0.001 rad/s. These fact indicates the accuracy of higher than 95% has been achieved. Copyright © 2015 Praise Worthy Prize S.r.l. - All rights reserved.

**Keywords:** AUV, EnKF-SR, Linear System, Trajectory Estimation

### Nomenclature

AUV	Autonomous Underwater Vehicle
DOF	Degree of Freedom
SVD	Singular Value Decomposition
EnKF-SR	Ensemble Kalman Filter Square Root
SNAME	The Society of Naval Architects and Marine Engineers
$\eta = [\eta_1^T, \eta_2^T]^T$	The position and orientation vector in the earth-fixed coordinates
$\eta_1 = [x, y, z]^T$	The linear position vector in the earth-fixed coordinates
$\eta_2 = [\phi, \theta, \psi]^T$	The angular position vector in the earth-fixed coordinates
$v = [v_1^T, v_2^T]^T$	The linear and angular velocity vector in the body-fixed coordinates
$v_1 = [u, v, w]^T$	The linear velocity vector in the body-fixed coordinates
$v_2 = [p, q, r]^T$	The angular velocity vector in the body-fixed coordinates
$\tau = [\tau_1^T, \tau_2^T]^T$	The forces and moments acting on the vehicle in the body-fixed coordinates
$\tau_1 = [X, Y, Z]^T$	The forces acting on the vehicle in the body-fixed coordinates
$\tau_2 = [K, M, N]^T$	The moments acting on the vehicle in the body-fixed coordinates
$[x_G, y_G, z_G]$	The AUV's center of gravity in body fixed coordinates
$[I_x, I_y, I_z]$	The moments of inertia about the X, Y, Z axes respectively

$f_1, f_2, f_3, f_4, f_5, f_6$	Surge, Sway, Heave, Roll, Pitch and Yaw for Function in Jacobian Matrix
$a_1, a_2, \dots, g_6$	Component of Matrix $A$ (Result of linearization using Jacobian Matrix)
$A_1, A_2, \dots, G_6$	Component of Matrix $B$ (Result of linearization using Jacobian Matrix)

### I. Introduction

Geographical area of Indonesia consists of islands and waters. Approximately two-thirds of the total area of Indonesia is water. Its strategic position, tropical climate and abundant natural resources offer high economic potential as well as national defensive potential, thus sophisticated underwater robotics technology is required to keep both national security and sea treasure of Indonesia. Underwater robotics technology currently being developed is an Autonomous Underwater Vehicle (AUV). AUV is capably underwater vehicle in moving automatically without direct control by humans according to the trajectory.

AUV can be used for underwater exploration, mapping, underwater defense system equipment, sensor off board submarines, inspection of underwater structures, natural resources and the condition of the Earth's surface plates etc [1]. Two important things required to analyze the Autonomous Underwater Vehicle (AUV) that is Earth Fixed Frame (EFF) and Body Fixed Frame (BFF) [2].



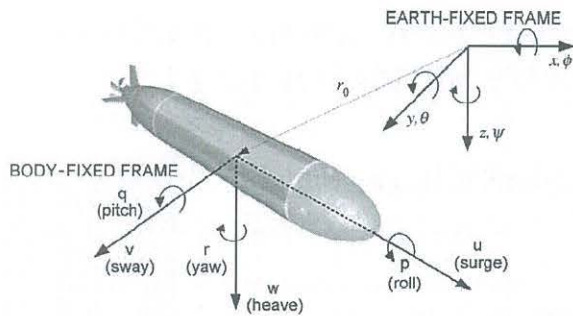


Fig. 1. 6 DOF in AUV

In a great number of envisioned mission scenarios, AUV will be need to follow inertial reference trajectory accurately [3]. To achieve that purpose, the navigation system must be designed and implemented on AUV.

One of basic Navigation system is trajectory estimation was was introduced in the 1961s and the most popular of estimation methods is the Kalman Filter.

Kalman filter is method of a state variable estimation from linear discrete dynamic system which minimizes the estimation error covariance [4], [12]-[15]. Another approximation is an extension of the Kalman filter called Ensemble Kalman Filter (EnKF) and Ensemble Kalman Filter Square Root (EnKF-SR).

In the EnKF method, the algorithm is executed by generating a number of specific ensemble to calculate the mean and covariance error state variables [5]. Ensemble Kalman Filter Square Root (EnKF-SR) is development of EnKF algorithm which Square root scheme is one scheme can be implemented in correction step [6].

The main contribution of this paper is trajectory estimation of linear AUV SEGOROGENI ITS system with Ensemble Kalman Filter Square Root (EnKF-SR). Linear model is obtained by linearizing nonlinear 6 DOF AUV model with Jacobian matrix. Linear system is platform to make trajectory estimation. The result of this paper is numeric simulation by comparing real trajectory and the result of trajectory estimation to get a small root mean square error (RMSE).

This paper consists of three types of simulations which the first, second and third simulation by generate 100, 200 and 300 ensemble. Profile of SEGOROGENI ITS depicted in Fig. 2.

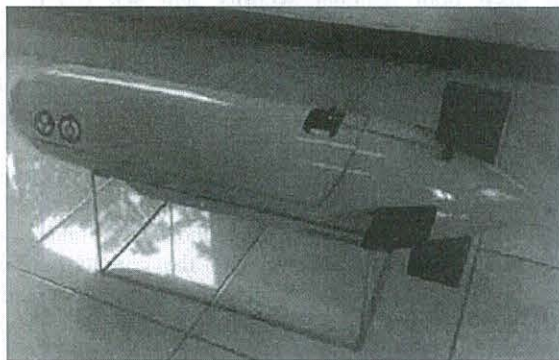


Fig. 2. Profile of AUV SEGOROGENI ITS

## II. Mathematical Model

Two important things required to analyze the Autonomous Underwater Vehicle (AUV) that is Earth Fixed Frame (EFF) and Body Fixed Frame (BFF) (Yang, 2007) [2]. EFF is used to describe the position and orientation of the AUV with the position of the x axis to the north, the y-axis to the east and the z-axis toward the center of the earth while BFF is used to describe the speed and acceleration of the AUV with the starting point at the center of gravity. x-axis to the ship's bow, the positive y axis direct to the right side of the ship and the positive z-axis direct [7], [8]. Motion of AUV have 6 DOF where 3 DOF for translational motion and 3 DOF for rotational motion in point x, y and z are listed in Table I.

TABLE I  
NOTATION OF AUV MOTION AXIS [9]

DOF	Translational And Rotational	Force/ Moment	Linear and Angular Velocity	Potition/ Angle Euler
1	Surge	$X$	$U$	$x$
2	Sway	$Y$	$V$	$y$
3	Heave	$Z$	$W$	$z$
4	Roll	$K$	$P$	$\phi$
5	Pitch	$M$	$Q$	$\theta$
6	Yaw	$N$	$R$	

The dynamics of the AUV there are external forces influencing the movement follows as [9]:

$$\tau = \tau_{hydrostatic} + \tau_{addedmass} + \tau_{drag} + \tau_{lift} + \tau_{control} \quad (1)$$

$$\begin{aligned} \eta &= [\eta_1^T, \eta_2^T]^T, \eta_1 = [x, y, z]^T, \eta_2 = [\phi, \theta, \psi]^T \\ v &= [v_1^T, v_2^T]^T, v_1 = [u, v, w]^T, v_2 = [p, q, r]^T \\ \tau &= [\tau_1^T, \tau_2^T]^T, \tau_1 = [X, Y, Z]^T, \tau_2 = [K, M, N]^T \end{aligned} \quad (2)$$

where  $\eta$  vector position the position and orientation of the EFF,  $v$  vector velocity of linear and angular of the BFF, the position and orientation of the BFF, and  $\tau$  description of force and moment in AUV of the BFF.

By combining equations hydrostatic, lift, added mass, drag, thrust and assuming a diagonal tensor of inertia ( $I_o$ ) is zero then the total forces and moments of models obtained from the following [2].

General equation of motion in 6-DOF AUV consists of translational and rotational as follows [2]:

Surge:

$$\begin{aligned} m[\dot{u} - vr + wq - x_G(q^2 + r^2) + y_G(pq - \dot{r}) + z_G(pr + \dot{q})] = \\ X_{|u|u}|u| + X_{\dot{u}}\dot{u} + X_{wq}wq + X_{qq}qq + X_{vr}vr + X_{rr}rr + X_{prop} \end{aligned} \quad (3)$$

Sway:

$$\begin{aligned} m[\dot{v} - wp + ur - y_G(r^2 + p^2) + z_G(qr - \dot{p}) + x_G(pq + \dot{r})] = \\ Y_{res} + Y_{|v|v}|v| + Y_{|r|r}|r| + Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + Y_{ur}ur + Y_{wp}wp + Y_{pq}pq + Y_{uv}uv + Y_{uu}\delta_r u^2 \delta_r \end{aligned} \quad (4)$$

Heave:

$$m[\dot{w} - uq + vp - z_G(p^2 + q^2) + x_G(rp - \dot{q}) + y_G(rq + \dot{p})] = Z_{res} + Z_{|w|w}w|w| + Z_{|q|q}q|q| + Z_{\dot{w}}\dot{w} + Z_{\dot{q}}\dot{q} + Z_{uq}uq + Z_{vp}vp + Z_{rp}rp + Z_{uw}uw + Z_{uu\delta_s}u^2\delta_s \quad (5)$$

Roll:

$$I_x\dot{p} + (I_z - I_y)qr + m[y_G(\dot{w} - uq + vp) - z_G(\dot{v} - wp + ur)] = K_{res} + K_{p|p|p|p|} + K_{\dot{p}}\dot{p} + K_{prop} \quad (6)$$

Pitch:

$$I_y\dot{q} + (I_x - I_z)rp + m[z_G(\dot{u} - vr + wq) - x_G(\dot{w} - uq + vp)] = M_{res} + M_{w|w|w|w|} + M_{|q|q|q|q|} + M_{\dot{w}}\dot{w} + M_{\dot{q}}\dot{q} + M_{uq}uq + M_{vp}vp + M_{rp}rp + M_{uw}uw + M_{uu\delta_s}u^2\delta_s \quad (7)$$

Yaw:

$$I_z\dot{r} + (I_y - I_x)pq + m[x_G(\dot{v} - wp + ur) - y_G(\dot{u} - vr + wq)] = N_{res} + N_{v|v|v|v|} + N_{r|r|r|r|} + N_{\dot{v}}\dot{v} + N_{\dot{r}}\dot{r} + N_{ur}ur + N_{wp}wp + N_{pq}pq + N_{uv}uv + N_{uu\delta_r}u^2\delta_r \quad (8)$$

Translational motion  $u, v$  and  $w$  are representation of surge, sway and heave. Rotational motion  $p, q$  and  $r$  are representation of roll, pitch and yaw.

This type of AUV SEGOROGENI ITS using only one

propeller on the tail AUV which will produce  $x_{prop}$  and additional moments  $K_{prop}$ . External forces and moments acting on the AUV are the hydrostatic force, thrust and hydrodynamic force and where every object in the water will have a hydrostatic force consisting of gravity and buoyancy forces.

While hydrodynamic component consists of added mass, drag and lift. Specification of AUV SEGOROGENI ITS in Table II.

TABLE II SPECIFICATION OF AUV SEGOROGENI ITS	
Weight	15 kg
Overall Length	980 mm
Beam	180 mm
Controller	Ardupilot Mega 2.0
Communication	Wireless Xbee 2.4 GHz
Camera	TTL Camera
Battery	Li-Pro 11,8 V
Propulsion	12V motor DC
Propeller	3 Blades OD : 40 mm
Speed	1,94 knots (1m/s)

### III. Linearization

In this paper the nonlinear system of AUV model can be linearized with Jacobian matrix where the nonlinear AUV system in general as follows:

$$\begin{aligned} \dot{x}(t) &= f(x(t), u(t), t) \\ y(t) &= g(x(t), u(t), t) \end{aligned} \quad (9)$$

So the Jacobian matrix is formed as follows [10]:

$$\frac{\partial f(\bar{x}, \bar{u}, t)}{\partial x} = \begin{bmatrix} \frac{\partial f_1(\bar{x}, \bar{u}, t)}{\partial x_1} & \frac{\partial f_1(\bar{x}, \bar{u}, t)}{\partial x_2} & \dots & \frac{\partial f_1(\bar{x}, \bar{u}, t)}{\partial x_n} \\ \frac{\partial f_2(\bar{x}, \bar{u}, t)}{\partial x_1} & \frac{\partial f_2(\bar{x}, \bar{u}, t)}{\partial x_2} & \dots & \frac{\partial f_2(\bar{x}, \bar{u}, t)}{\partial x_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_n(\bar{x}, \bar{u}, t)}{\partial x_1} & \frac{\partial f_n(\bar{x}, \bar{u}, t)}{\partial x_2} & \dots & \frac{\partial f_n(\bar{x}, \bar{u}, t)}{\partial x_n} \end{bmatrix} \quad (10)$$

So Eq. (3) - (8) can be expressed as follows:

$$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & -\frac{m z_G}{I_x - K_{\dot{p}}} & \frac{m y_G}{I_x - K_{\dot{p}}} & 0 & 0 & 0 \\ \frac{m z_G}{I_y - M_{\dot{q}}} & 0 & -\frac{(m x_G + M_{\dot{w}})}{I_y - M_{\dot{q}}} & 0 & 0 & 0 \\ -\frac{m y_G}{I_z - N_{\dot{r}}} & \frac{(m x_G - N_{\dot{v}})}{I_z - N_{\dot{r}}} & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & \frac{m z_G}{m - X_{\dot{u}}} & \frac{-m y_G}{m - X_{\dot{u}}} \\ -\frac{m z_G}{m - Y_{\dot{v}}} & 0 & \frac{(m x_G - Y_{\dot{r}})}{m - Y_{\dot{v}}} \\ \frac{m y_G}{m - Z_{\dot{w}}} & -\frac{(m x_G + Z_{\dot{q}})}{m - Z_{\dot{w}}} & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \\ \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \\ f_6 \end{bmatrix} \quad (11)$$



where  $f_1, f_2, f_3, f_4, f_5, f_6$  expressed as follows:

$$f_1 = \frac{X_{res} + X_{|u|u}|u| + X_{wq}wq + X_{qq}qq + X_{vr}vr + X_{rr}rr + X_{prop} + m[-vr + wq - x_G(q^2 + r^2) + pq y_G + pr z_G]}{m - X_{\dot{u}}} \quad (12)$$

$$f_2 = \frac{Y_{res} + Y_{|v|v}|v| + Y_{r|r}|r| + Y_{ur}ur + Y_{wp}wp + Y_{pq}pq + Y_{uv}uv + Y_{uu\delta_r}u^2\delta_r - m[-wp + ur - y_G(r^2 + p^2) + qr z_G + pq x_G]}{m - Y_{\dot{v}}} \quad (13)$$

$$f_3 = \frac{Z_{res} + Z_{|w|w}|w| + Z_{q|q}|q| + Z_{uq}uq + Z_{vp}vp + Z_{rp}rp + Z_{uw}uw + Z_{uu\delta_s}u^2\delta_s - m[-uq + vp - z_G(p^2 + q^2) + rp x_G + rq y_G]}{m - Z_{\dot{w}}} \quad (14)$$

$$f_4 = \frac{K_{res} + K_{p|p}|p| + K_{prop} - ((I_z - I_y)qr + m[y_G(-uq + vp) - z_G(-wp + ur)])}{I_x - K_{\dot{p}}} \quad (15)$$

$$f_5 = \frac{M_{res} + M_{w|w}|w| + M_{q|q}|q| + M_{uq}uq + M_{vp}vp + M_{rp}rp + M_{uw}uw + M_{uu\delta_s}u^2\delta_s - ((I_x - I_z)rp + m[z_G(-vr + wq) - x_G(-uq + vp)])}{I_y - M_{\dot{q}}} \quad (16)$$

$$f_6 = \frac{N_{res} + N_{v|v}|v| + N_{r|r}|r| + N_{ur}ur + N_{wp}wp + N_{pq}pq + N_{uv}uv + N_{uu\delta_r}u^2\delta_r - ((I_y - I_z)pq + m[x_G(-wp + ur) - y_G(-vr + wq)])}{I_z - N_{\dot{r}}} \quad (17)$$

Furthermore linear system is obtained as follows [11]:

$$\begin{aligned} \dot{x}(t) &= A x(t) + Bu(t) \\ y(t) &= Cx(t) + Du(t) \end{aligned} \quad (18)$$

with:

$$A = J_x = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & -\frac{mz_G}{I_x - K_{\dot{p}}} & \frac{my_G}{I_x - K_{\dot{p}}} & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -\frac{mz_G}{I_y - M_{\dot{q}}} & \frac{my_G}{I_y - M_{\dot{q}}} & 0 \\ 0 & -\frac{mz_G}{I_x - K_{\dot{p}}} & \frac{my_G}{I_x - K_{\dot{p}}} & 0 & 0 & 0 \\ \frac{mz_G}{I_y - M_{\dot{q}}} & 0 & -\frac{(mx_G + M_{\dot{w}})}{I_y - M_{\dot{q}}} & 0 & 0 & 0 \\ -\frac{my_G}{I_z - N_{\dot{r}}} & \frac{(mx_G - N_{\dot{v}})}{I_z - N_{\dot{r}}} & 0 & 0 & 0 & 0 \end{bmatrix}^{-1} \quad (19)$$

$$\begin{bmatrix} a_1 & b_1 & c_1 & d_1 & e_1 & g_1 \\ a_2 & b_2 & c_2 & d_2 & e_2 & g_2 \\ a_3 & b_3 & c_3 & d_3 & e_3 & g_3 \\ a_4 & b_4 & c_4 & d_4 & e_4 & g_4 \\ a_5 & b_5 & c_5 & d_5 & e_5 & g_5 \\ a_6 & b_6 & c_6 & d_6 & e_6 & g_6 \end{bmatrix}$$

$$B = J_u = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & -\frac{m z_G}{I_x - K_{\dot{p}}} & \frac{m y_G}{I_x - K_{\dot{p}}} & 0 & 0 & 0 \\ \frac{m z_G}{I_y - M_{\dot{q}}} & 0 & -\frac{(m x_G + M_{\dot{w}})}{I_y - M_{\dot{q}}} & 0 & 0 & 0 \\ -\frac{m y_G}{I_z - N_{\dot{r}}} & \frac{(m x_G - N_{\dot{v}})}{I_z - N_{\dot{r}}} & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & \frac{m z_G}{m - X_{\dot{u}}} & \frac{-m y_G}{m - X_{\dot{u}}} \\ -\frac{m z_G}{m - Y_{\dot{v}}} & 0 & \frac{(m x_G - Y_{\dot{r}})}{m - Y_{\dot{v}}} \\ \frac{m y_G}{m - Z_{\dot{w}}} & -\frac{(m x_G + Z_{\dot{q}})}{m - Z_{\dot{w}}} & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}^{-1} \quad (20)$$

$$C = \begin{bmatrix} A_1 & B_1 & C_1 & D_1 & E_1 & G_1 \\ A_2 & B_2 & C_2 & D_2 & E_2 & G_2 \\ A_3 & B_3 & C_3 & D_3 & E_3 & G_3 \\ A_4 & B_4 & C_4 & D_4 & E_4 & G_4 \\ A_5 & B_5 & C_5 & D_5 & E_5 & G_5 \\ A_6 & B_6 & C_6 & D_6 & E_6 & G_6 \end{bmatrix} \quad \text{and } D = 0 \quad (21)$$

So:

$$\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \\ \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = A \begin{bmatrix} u \\ v \\ w \\ p \\ q \\ r \end{bmatrix} + B \begin{bmatrix} X_{prop} \\ \delta_r \\ \delta_s \\ K_{prop} \\ \delta_s \\ \delta_r \end{bmatrix} \quad (22)$$

and then discretized can be show:

$$\begin{bmatrix} u_{k+1} \\ v_{k+1} \\ w_{k+1} \\ p_{k+1} \\ q_{k+1} \\ r_{k+1} \end{bmatrix} = A \begin{bmatrix} u_k \\ v_k \\ w_k \\ p_k \\ q_k \\ r_k \end{bmatrix} + B \begin{bmatrix} X_{prop} \\ \delta_r \\ \delta_s \\ K_{prop} \\ \delta_s \\ \delta_r \end{bmatrix} \quad (23)$$

If we write completely, so the discrete models in Eq. (23) can be written generally in a linear function bellow:

$$x_{k+1} = f(x_k, u_k) \quad (24)$$

Due to some assumptions, the stochastic factor in noise must be added to each equations. Thus Eq. (23) can be formulated as follows [4]:

$$x_{k+1} = f(x_k, u_k) + w_k \quad (25)$$

$$z_k = Hx_k + v_k \quad (26)$$

whereas  $f(x_k, u_k)$  is nonlinear or linear function will be applied Ensemble Kalman Filter Square Root (EnKF-SR)

Algorithm.

The system noise  $w_k$  and measurement noise  $v_k$  are generated by computer and usually normally distributed, so the mean zero.

Generally,  $Q_k$  states the system noise varians and  $R_k$  states the measurement noise varians. Both are depend on time [4].

#### IV. Ensemble Kalman Filter Square Root

This section present EnKF-SR algorithm to estimated nonlinear or linear dynamic system and measurement model, the algorithm *Ensemble Kalman Filter Square Root* (EnKF-SR) can be seen [6]:

*Model system and measurement model*

$$x_{k+1} = f(x_k, u_k) + w_k \quad (27)$$

$$z_k = Hx_k + v_k \quad (28)$$

$$w_k \sim N(0, Q_k), \quad v_k \sim N(0, R_k) \quad (29)$$

##### 1. Initialization

Generate  $N$  ensemble as the first guess  $\bar{x}_0$ :

$$x_{0,i} = [x_{0,1} \quad x_{0,2} \quad \dots \quad x_{0,N}] \quad (30)$$

The first Mean *Ensemble*:

$$\bar{x}_{0,i} = x_{0,i} \mathbf{1}_N \quad (31)$$



The first *Ensemble* error:

$$\tilde{x}_{0,i} = x_{0,i} - \bar{x}_{0,i} = x_{k,i}(I - 1_N) \quad (32)$$

2. Time Update:

$$\hat{x}_{k,i}^- = f(\hat{x}_{k-1,i}, u_{k-1,i}) + w_{k,i} \quad (33)$$

where:

$$w_{k,i} = N(0, Q_k)$$

Mean *Ensemble*:

$$\bar{x}_{k,i}^- = \hat{x}_{k,i}^- 1_N \quad (34)$$

Error *Ensemble*:

$$\tilde{x}_{k,i}^- = \hat{x}_{k,i}^- - \bar{x}_{k,i}^- = \hat{x}_{k,i}^- (I - 1_N) \quad (35)$$

3. Measurement Update:

$$z_{k,i} = Hx_{k,i} + v_{k,i} \quad (36)$$

where:

$$v_{k,i} \sim N(0, R_k)$$

$$\begin{aligned} S_k &= H\tilde{x}_{k,i}^- E_k = (v_1, v_2, \dots, v_N) \\ C_k &= S_k S_k^T + E_k E_k^T \end{aligned} \quad (37)$$

Mean *Ensemble*:

$$\bar{x}_{k,i} = \bar{x}_{k,i}^- + \tilde{x}_{k,i}^- S_k^T C_k^{-1} (\bar{z}_{k,i} - H\bar{x}_{k,i}^-) \quad (38)$$

Square Root Scheme:

- eigenvalue decomposition from:

$$C_k = U_k \Lambda_k U_k^T \quad (39)$$

- determine matrix:

$$M_k = \Lambda_k^{\frac{1}{2}} U_k^T S_k^- \quad (40)$$

- determine SVD from:

$$M_k = Y_k L_k V_k^T \quad (41)$$

Ensemble Error:

$$\tilde{x}_{k,i} = \tilde{x}_{k,i}^- V_k (I - L_k L_k^T)^{\frac{1}{2}} \quad (42)$$

Ensemble Estimation:

$$\hat{x}_{k,i} = \tilde{x}_{k,i} + \bar{x}_{k,i} \quad (43)$$

To evaluate of estimation result accuracy from EnKF algorithm, can be show with calculate Root Mean Square Error (RMSE) [6]:

$$RMSE = \sqrt{\frac{\sum_i^n (X_{obs,i}(k) - X_{model,i}(k))^2}{n}} \quad (44)$$

with:

$X_{obs,i}(k)$  = observation data;

$X_{model,i}(k)$  = model data;

$n$  = iteration.

## V. Computational Result

This simulation has been carried out by implementing an algorithm Ensemble Kalman Filter (EnKF) in the AUV model.

The result of simulation will be evaluated and compared with real condition, estimaton result with EnKF. This simulation consist of three types of simulations. in which the first, second, third simulation by generate 100,200 and 300 ensemble. Simulations have been done by assuming surge ( $u$ ), sway ( $v$ ), heave ( $w$ ), roll ( $p$ ), pitch ( $q$ ) and yaw ( $r$ ).

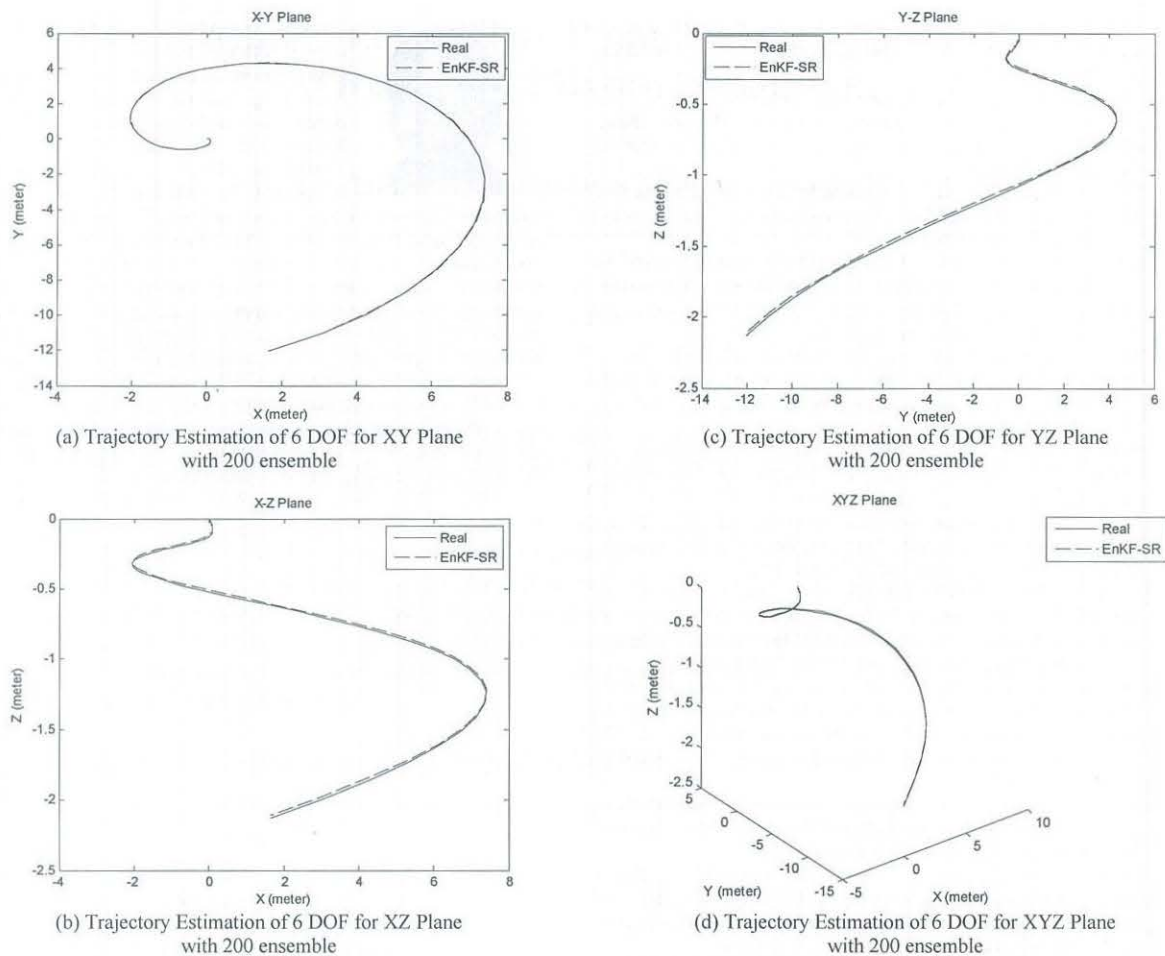
The value of  $\Delta t$  has been used was  $\Delta t = 0,1$ . Initial condition has been used were  $u_0 = 0 \text{ m}$ ,  $v_0 = 0 \text{ m}$ ,  $w_0 = 0 \text{ m}$ ,  $p_0 = 0 \text{ rad}$ ,  $q_0 = 0 \text{ rad}$  and  $r_0 = 0 \text{ rad}$ .

Figs. 3 show result of trajectory estimation AUV by generate 200 ensemble. Fig. 3(a) shows the result of trajectory estimation in XY plane, Fig. 3(b) in XZ plane, Fig. 3(c) in YZ plane and Fig. 3(d) in XYZ plane.

Fig. 3(a) shows result of trajectory estimation highly accurate with tracking error of surge 0,0094 m/s and accuracy of 99,22%. Tracking error of sway 0,011 m/s and accuracy of 97,8%. AUV moves forward and turns around within XY plane to the right direction reaching more or less 270 degrees. Surge motion is influenced by the propeller  $X_{prop}$ . The sway motion is influenced by vertical fin or rudder  $\delta_r$ . The angle of rudder position will affect sway motion of AUV so we need control system for control the angle of rudder position.

Fig. 3(b) shows result of trajectory estimation highly accurate with tracking error of surge 0,0094 m/s and accuracy of 99,22%. Tracking error of heave 0,0081 m/s and accuracy of 96,8%. AUV dives moving right and left to the depth of 2,2 meters. The heave motion is influenced by horizontal fin or stern  $\delta_s$ . The angle of stern position will affect heave motion of AUV, so we need control system for control The angle of stern position. Fig. 3(c) shows the result of trajectory estimation highly accurate for YZ plane. Fig. 4(d) shows result of trajectory estimation highly accurate for XYZ Plane with tracking error of translational motion 0,009 m/s and accuracy of 97,39%. Tracking error of rotational motion 0,001 rad/s and accuracy of 99,97%.

In general as seen in the Table III, the results of the three simulations were highly accurate. The first simulation by generate 100 ensemble with tracking error of translational motion 0,0093 m/s or accuracy of 97,39% and rotational motion 0,0012 rad/s or accuracy of 99,978%.



Figs. 3. Trajectory estimation AUV by generate 200 ensemble

The second simulation by generates 200 ensemble with tracking error of translational motion 0,0096 m/s or accuracy of 97,94% and rotational motion 0,0015 rad/s or accuracy of 99,96%. The third simulation by generate 300 ensemble with tracking error of translational motion 0,0095 m/s or accuracy of 97,31% and rotational motion 0,0019 rad/s or accuracy of 99,94%. Time simulation of the three simulation results with 100 ensemble faster than 200 and 300 ensemble because more ensemble generated the longer time simulation

TABLE III  
SIMULATION RESULTS

	100 ens RMSE	Accuracy	200ens RMSE	Accuracy	300ens RMSE	Accuracy
Surge	0.0082 m/s	99,41%	0.0094 m/s	99,22%	0.0083 m/s	99,3%
Sway	0.01 m/s	97,77%	0.0112 m/s	97,8%	0.0101 m/s	97,76%
Heave	0.0096 m/s	94,98%	0.0081 m/s	96,8%	0.01085 m/s	94,86%
Roll	0.0012 rad/s	99,99%	0.0012 rad/s	99,95%	0.0019 rad/s	99,93%
Pitch	0.0012 rad/s	99,97%	0.0017 rad/s	99,96%	0.0018 rad/s	99,95%
Yaw	0.001 rad/s	99,97%	0.0015 rad/s	99,96%	0.0020 rad/s	99,95%
Time	0.6875 s		1.0469 s		1.4531 s	

## VI. Conclusion

Based on analysis of the three simulation results, EnKF-SR method could be applied to estimate of linear system trajectory of AUV SEGOROGENI ITS with considerably high accuracy. Of the three simulation by generating both 100, 200 and 300 ensembles, the estimation results were all accurate. Square root scheme is one scheme can be implemented in the EnKF.

This scheme can affect the estimation results because it implemented in correction step in EnKF Algorithm.

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1970-8734(201511)9:6;1-G